

Decadal variation of the North Atlantic meridional heat transport and its relation to atmospheric processes

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[1] The effects of the meridional heat transport in the North Atlantic Ocean (HTR) on the north hemispheric climate are studied using the results of the coupled model ECHAM5/MPI-OM. Significant correlations exist between HTR and atmospheric processes over the Nordic Seas and the Eurasian continent only for low (periods longer than 40 years) and intermediate frequency variations (periods between 25 and 40 years). A positive HTR anomaly at 30°N is highly correlated with turbulent heat fluxes around 50°N. The transport through 70°N is directly related to the fluxes over the Nordic seas. From the correlation pattern with the atmospheric surface temperature and pressure one can conclude that the heat anomalies propagate along the cyclone tracks towards northeast over the Eurasian continent. The HTR anomalies are negatively correlated with the pressure over the Nordic seas and with the winter time anticyclone intensity over Siberia. **Citation:** Martin, T., and E. Ruprecht (2007), Decadal variation of the North Atlantic meridional heat transport and its relation to atmospheric processes, *Geophys. Res. Lett.*, 34, L04703, doi:10.1029/2006GL028438.

1. Introduction

[2] The meridional energy transport in the atmosphere and the ocean as consequence of the global north-south radiation imbalance and the interaction between the two climate components are fundamental processes governing the climate state of the earth and its variability. In particular, the Nordic seas north of Europe owe their relative high temperatures to the warm surface currents of the Gulf and North Atlantic stream. There is recently an excited discussion amongst climatologists and even in the public, about the impact of changes of these currents which may result from anthropogenic activities, on the climate, in particular of Europe [Latif *et al.*, 2006].

[3] Low frequency variability of the meridional ocean energy transport is mainly related to changes in the thermohaline circulation which has its dominant variations in the multi-decadal frequency [Delworth and Mann, 2000]. Such relationships, however, can be derived only from model results since long time series of direct observations are not available. Jungclauss *et al.* [2005] have analyzed a 500-yr control integration of the coupled climate model ECHAM5/MPI-OM. They found for the North Atlantic meridional overturning circulation a multi-decadal variation with a period of approximately 70–80 years. These low

frequency variations are in phase with the fluctuations of the North Atlantic meridional heat transport. The oscillation is due in their model to processes in the subpolar convection region.

[4] Jungclauss *et al.* [2005] have concentrated their analysis on the low frequency processes in the ocean, in this study we analyzed the effect of the variability of the North Atlantic meridional heat transport on atmospheric winter processes of the Northern hemisphere. During winter time, there exist in the atmosphere of the northern hemisphere three major pressure systems: Icelandic low (IL) with its centre south of Iceland, Siberian high (SH) centred near 45°N, 90°–100°E, and Aleutian low (AL) near the Gulf of Alaska. Observations imply a variability of the Siberian high on interannual and decadal time scales. However, the periods itself, as well as the mechanisms are still in discussion. Sahsamanoglou *et al.* [1991] derived periodicities of less than 4.5 years and at 58 years. D'Arrigo *et al.* [2005] found low frequency variability between 17 yr and 41 yr determined from tree rings. Gong and Ho [2002] analyzed from a quite limited time series a weakening of the SH intensity during the last 20 years. Panagiotopoulos *et al.* [2005] conclude from different data sets a negative trend after 1928 between -0.16 hPa/decade and -0.54 hPa/decade and after 1978 a trend of up to -2.6 hPa per decade. The Icelandic low is connected with the Azores high within the process of the North Atlantic Oscillation (NAO). Inter-annual and decadal variability of the NAO and with it of the Icelandic low is identified by several authors as an interaction mechanism between ocean and atmosphere [e.g., Eden and Jung, 2001]. Since the dominant atmospheric time scales are intra-annual, it is believed that longer atmospheric time scales are the product of ocean forcing [Delworth and Mann, 2000]. For this reason we will concentrate here on the longer time scales: How does decadal variability of the meridional energy transport in the North Atlantic Ocean effect the atmospheric circulation, here in particularly the three dominant pressure system mentioned above?

2. Model Data and Analysis Methods

[5] The long time data for this study are provided by the results of a 500 year control run of the coupled climate model ECHAM5/MPI-OM [Jungclauss *et al.*, 2005]. The simulation with horizontal resolution of T42 and 19 vertical layers in the atmosphere and 23 layers in the ocean is performed with fixed greenhouse gas concentration on the level corresponding to that of 1990. The model maintains a reasonably stable climate without flux adjustment. We analyzed monthly mean atmospheric fields and annual means of the meridional heat transport in the Atlantic Ocean for the last 450 years of the control run. The latter is implied

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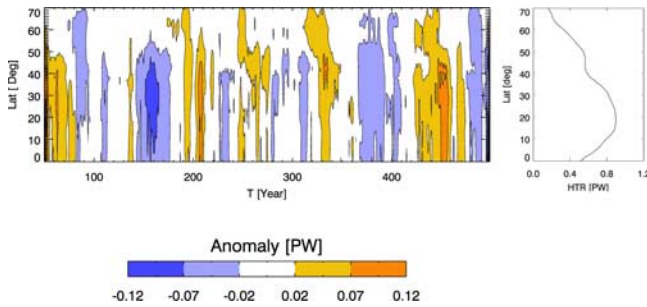


Figure 1. Meridional heat transport in the Atlantic Ocean as function of latitude in PW; right: long term zonal mean profile, left: zonal mean of annual anomalies (6 year running mean).

by the net surface atmosphere-ocean heat flux [Jungclauss *et al.*, 2005].

[6] The mean profile of the meridional ocean heat transport (HTR) in the Atlantic Ocean with 0.52 PW across the Equator, and the maximum of 0.9 PW between 15° and 20°N is in agreement with recent analyses by Trenberth and Caron [2001] (Figure 1, right) and compare well with direct observations although the model slightly underestimates the northward heat transport. Variations are in phase in the region between the equator and about 50°N. Further north, however, they precede the once in the tropics, and they have much smaller amplitudes (Figure 1, left). The spectral analysis of the HTR at 30°N (not shown here) provides well expressed variability over the whole frequency range, with minima at 40 years, 25 years and 8.3 years. According to this, we classify the spectral variability into three time scales representing characteristic parts of the variance spectrum: low frequency represents the variability of periods longer than 40 years, intermediate frequency covers the interval between 40 years and 25 years, followed by high frequency with periods shorter than 25 years. A digital filter has been applied on the monthly mean atmospheric fields and annual means of the meridional heat transport in the Atlantic Ocean for the last 450 years of the control run for low-pass respectively high-pass filtering. The residual of filtering process has been identified as the intermediate time series. In general the retrieved results are very robust against a slight shift of the interval boundaries.

[7] In order to determine relationships between HRT and atmospheric processes we used various indices. The Arctic Oscillation index (AO) is represented by the 1. Principal component (Pc) of an EOF analysis of the surface pressure field (SLP) north of 20°N. The North Atlantic Oscillation index (NAO) has been derived from the differences of the normalized December to February mean sea-level pressure between the grid point close to Azores (26°W 38°N) and Iceland (23°W 65°N) [Rodwell *et al.*, 1999]. Pressure indices are defined for the Greenland-Island-Norwegian Sea (GIN) as mean SLP averaged over the area 30.9°W–39.4°E and 60.0°N–76.7°N, and for the Barents Sea/Kara Sea (BK) region, 19.7°E–101.3°E and 85.1°N–71.2°N. According to Trenberth and Hurrell [1994] we derive an mean SLP index for the North Pacific region (NP) as an average over the region of 30°N–60°N, 160°E–140°W.

The temporal variability of the SH is often described in the literature by the Siberian high intensity (SHI) index derived from the normalized area mean pressure anomaly during the winter month, related to the region 40°N–65°N, 80°E–120°E, [e.g., Panagiotopoulos *et al.*, 2005; D'Arrigo *et al.*, 2005]. Investigations of Sahsamanoglou *et al.* [1991] suggest that the center of the SH is shifted to the west, when the center pressure weakens. The selected area for the determination of the SHI, however, includes the center of the SH in all situations.

3. Results

[8] Our investigation is focused on the winter period December to February. During these months the heat exchange between ocean and atmosphere can be very large in the mid and high latitudes, which is an excellent basis for investigation of the ocean-atmosphere interaction. The standard deviations of the two turbulent heat fluxes are of the same order of magnitude over the North Atlantic. Therefore, in the following we take only the total sum (sensible and latent heat flux) into account, although their spatial distribution differs.

[9] In the following, the dependency of the variation of atmospheric processes on the HRT variability will be described in terms of correlation coefficients r . With respect to the 95% confidence level, $r \geq 0.6$ is significant for the low frequency (40 years) and $r \geq 0.4$ for the intermediate part (25 years). Figure 2 shows the correlation pattern between the HTR at 30°N (HTR30, left) and at 70°N (HTR70, right), respectively with the total surface heat flux variation on time scales longer than 40 years. Since the HTR weakens northwards of 20°N the ocean must release heat into the atmosphere north of 20°N. The high positive correlation between HTR30 and the surface heat flux at about 50°N suggests that a positive energy anomaly which is transported through 30°N is mainly released to the atmosphere in the mid latitude (Figure 2, left). The region where the correlation coefficient has its maximum is known for its strong west winds. Here the polar front determines the cyclone tracks with east- and northwards moving disturbances. Thus, a possible connection between the heat

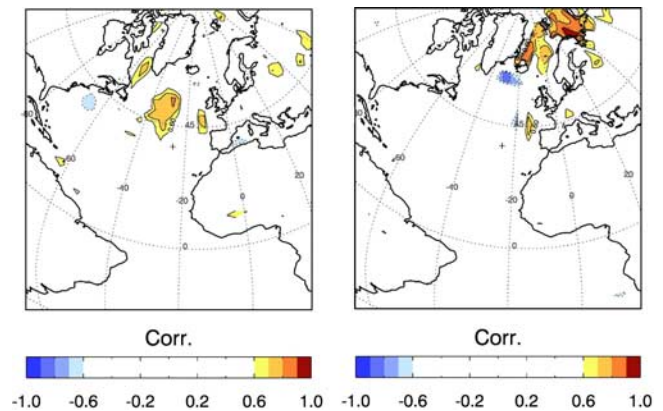


Figure 2. Correlation pattern of the low frequency HTR and the total (sensible and latent) ocean surface heat flux during winter (December–February): (left) HTR through 30°N and (right) HTR through 70°N.

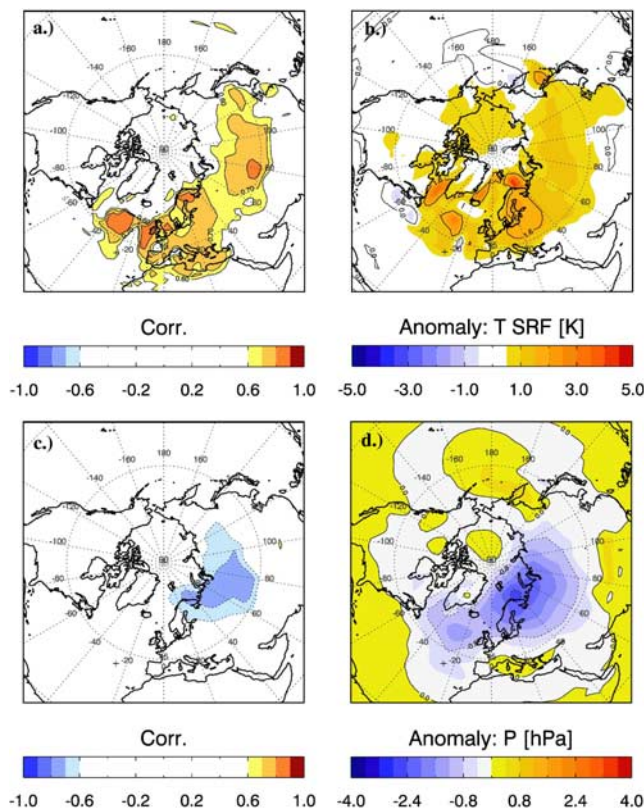


Figure 3. (left) Correlation analysis: Correlation coefficients between low frequency HTR30 and winter time (December–February) (a) surface temperature and (c) surface pressure (contour interval 0.1 starting with 0.6, -0.6 respectively). (right) Composite study: Differences between HTR30 high (anomalies larger than 0.5 standard deviation) and HTR30 low (anomalies smaller than -0.5 standard deviation) of (b) surface temperature and (d) pressure (contour interval 0.4 hPa).

transport in the ocean and these cyclones can be expected (although the cyclones are not analyzed in the model). However we conclude that the westerly winds and the east- and northward moving cyclones should be responsible for the transport of the ocean signal to the European and Asian continent and the eastern Arctic Seas. In contrast to the conditions at 30°N , the heat which is transported through 70°N is highly correlated with the heat release of the Arctic seas into the atmosphere. This indicates that low frequency changes of HTR70 are directly present in the Arctic atmosphere.

[10] The correlation pattern at Figure 3a shows a close relation between the low frequency HTR30 and surface temperatures at 50°N , the area of the correlation maximum between HTR30 and the heat flux. A high correlation is also found eastwards over the continent up to the center of the Siberian high. The correlation between HTR30 and the mean northern hemispheric (north of 20°N) exceeds 0.6 for low frequencies. In order to estimate a quantitative number we perform a composite relative to high HTR30 (larger than 0.5 standard deviation) and low HTR30 (smaller than -0.5 standard deviation). Figure 3b gives

the pattern of the temperature differences between high and low HTR30. The largest differences are found over NE Europe, GIN and Barents Sea with $\Delta T > 3$ K. But the whole North Asian continent is affected ($\Delta T > 1$ K). In contrast, the composites of the intermediate and high frequencies show no significant anomalies (not shown here).

[11] The question arises whether these relations between HTR and the thermal anomalies in the lower atmosphere also show up in the pressure anomaly patterns, in particular in the behavior of the three prominent pressure systems of the northern hemisphere: Icelandic low, Siberian high, and Aleutian low. The correlation of the low frequency variability of the HTR30 with the surface pressure field is given in Figure 3c. Significant negative correlations are found only over the Nordic seas and NW Europe. The composite (Figure 3d) reveals maximum amplitudes of up to 5 hPa over the Barents Sea. From Figures 3c and 3d and Figure 2a one can conclude that an increase of the oceanic heat transport through 30°N intensifies the storms over the North Atlantic from the region south of Iceland and extends the storm tracks towards east. On the other hand Figures 3a and 3c indicate that there are only small effects of ocean heat transport anomalies on the Pacific sector including the Aleutian low.

[12] From the dominating pressure systems only the Siberian high (SH) shows a large correlation with HTR30. During high HTR30 phases the Siberian anticyclone weakens, particularly in its western parts. The center itself shows only small anomalies in respect to the HTR30. Obviously the location of the center is independent of the HTR30 anomalies, whereas the spatial extension of the pressure system is reduced during periods of an intensified HTR30. The relationship between the low frequency variability of the HTR and the SH intensity has direct consequences for the understanding of the variability of the climate of the region. A weakened Siberian high pressure system has strong local effects with increasing surface temperatures and a slightly higher cloudiness. Our model results show significant decadal variability of the SHI index which are closely related to the variation of HTR. The obvious time lags will be discussed later. A significant trend over the total time period is not found.

[13] Table 1 summarizes results of the correlation analysis between the HTR and the mean surface pressure of different areas for decadal time scales. There exists no significant correlation between the meridional heat transport

Table 1. Correlation Coefficients of HTR and Regional Surface Level Pressure Indices During Winter (DJF)^a

Index	Total	Low	Intermediate
HTR 70°N , AO	0.03	0.12	0.45
HTR 30°N , NAO	-0.05	0.08	0.08
HTR 30°N , GIN	-0.1	-0.55	-0.33
HTR 70°N , GIN	-0.02	-0.39	-0.5
HTR 30°N , SH	-0.13	-0.75	-0.65
HTR 30°N , BK	-0.11	-0.48	-0.29
HTR 30°N , NP	0.08	0.05	0.49

^aBold numbers exceeds the 95% confidence level). LOW: $T > 40$ years (Confidence level at $T = 40$ years: $r > 0.6$ (95%); $r > 0.5$ (90%); Intermediate: 40 years $> T > 25$ years (Confidence level at $T = 25$ years: $r > 0.4$ (95%)).

and atmospheric parameters if all frequencies are included. The maximum correlation (-0.75) is found between HTR30 and the Siberian high for periods longer than 40 years. For the intermediate frequencies this correlation is still significant (-0.65) but the two values are uncorrelated for the unfiltered time series. The most significant correlation coefficients are found in the intermediate frequency interval: HTR70 is highly correlated with the mean surface pressure of the GIN Sea, and the variations of the transport through 30°N are connected to the pressure anomalies of the North Pacific (Aleutian low) beside to those of the Siberian high. The different results of the correlation analysis admit the following conclusion: There exists no direct connection through the Arctic seas between HTR through 30°N and the North Pacific; the correlation must be explained with relation through the Siberian high as a possible annular mode. This conclusion is also confirmed by the significant correlation between the SHI and the AO for intermediate time scales. The correlation pattern (Figures 3a and 3c) shows significant correlation between low frequency HTR30 and surface pressure at different grid points over the Arctic Seas (Barents-, Kara Sea) extending over the Eurasian continent. But the correlation coefficients are not significant any more if we carry out the correlation with the pressure indices of those regions, the average process weakens the connection.

[14] The correlation between the low frequency HTR and the turbulent surface heat flux varies with increasing latitude (Figure 2). Additionally to this, Figure 1 indicates a phase shift between the HTR anomalies at mid latitudes and at the polar region. In order to look in more details, we carried out lag correlations between HTR30 and the heat transport at 50°N and 70°N . The HTR anomalies at different latitudes are highly correlated; however, the correlation coefficient at lag zero decreases toward north. The correlation maximum is shifted towards positive lags (the northern HTR leads). The transport through 70°N (50°N) leads those at 30°N by 10 (3) years. We may conclude from this fact in agreement with the results of Jungclaus *et al.* [2005] that the low frequency variability of the thermohaline circulation has its source in the north starting with a downwelling. Variation of the downwelling convection has its origin mainly in the subpolar and polar regions. It takes several years before the signal of a downwelling intensification arrives at the tropics and intensifies the meridional overturning circulation and the heat transport. The lag correlation between the low frequency time series of HTR30 and the Siberian high index provides a lag time of 2 years which indicates that the subtropical and mid latitude anomalies of HTR have the most dominant effect on the conditions over the Eurasian continent.

[15] This leads directly to the question about a link between relevant processes steering the air-sea interaction in the Arctic region. We could not identify any atmospheric parameter which is significantly correlated with the low frequency HTR70 anomalies, although there exists a high correlation between the HTR at 70°N and the total turbulent heat fluxes in the same region, indicating a strong local ocean-atmosphere interaction. Obviously processes on a shorter timescale are more relevant e.g. are the AO and the pressure index of the GIN Seas are significantly correlated with the HTR70 at intermediate time scales. The

correlation even increases with a time lag: Correlation is at its maximum of $r = 0.48$ (AO), $r = -0.54$ (GIN) respectively, when the pressure indices leads HTR70 by 2 years.

4. Conclusion

[16] A statistically significant relation between the meridional energy transport in the North Atlantic ocean and atmospheric processes over the Nordic seas and the Eurasian continent exists only for decadal (larger than 25 years) time scales. That means, short time variability of HTR do not have a systematic effect on the atmosphere. Anomalies must exist for a longer period to have a significant impact on the atmosphere over the Nordic seas and the Eurasian continent.

[17] The low frequency anomalies of the meridional ocean heat transport in North Atlantic are largest at mid latitudes around 30°N . During the northern hemispheric winter, positive anomalies in the HTR30 are followed by an increase of the heat release from the ocean into the atmosphere at mid latitudes. Since the closest relation between HTR30 and the heat release to the atmosphere is found in the region of the storm tracks we conclude that the heat anomalies are transported by the cyclones eastwards. Thus, the HTR30 anomalies are significantly correlated to the low frequency temperature anomalies over the Nordic seas and the northern European and Asian continent. A positive HTR anomaly leads to a decrease of the mean surface pressure in the Barents Sea and Kara Sea region extension and intensification of the storm tracks, which could additionally result in a shift in the long term mean sea ice mass flux in the European Arctic [Martin and Martin, 2007]. For the processes over the continent a low frequency positive HRT anomaly is related to a weakening of the Siberian high pressure system. This low frequency variability of the SHI index should not be taken for a trend during the last century.

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